Abstract

Time Domain Reflectometry (TDR) and other in-situ and remote sensing dielectric methods for determining the soil water content had become standard in both research and practice in the last two decades. Limitations of existing dielectric methods in some soils, and introduction of new agricultural measurement devices or approaches based on soil dielectric properties mandate improved understanding of the relationship between the measured effective permittivity (dielectric constant) and the soil water content. Mounting evidence indicates that consideration must be given not only to the volume fractions of soil constituents, as most mixing models assume, but also to soil attributes and ambient temperature in order to reduce errors in interpreting measured effective permittivities. The major objective of the present research project was to investigate the effects of the soil geometrical attributes and interfacial processes (bound water) on the effective permittivity of the soil, and to develop a theoretical frame for improved, soil-specific effective permittivity – water content calibration curves, which are based on easily attainable soil properties. After initializing the experimental investigation of the effective permittivity – water content relationship, we realized that the first step for water content determination by the Time Domain Reflectometry (TDR) method, namely, the TDR measurement of the soil effective permittivity still requires standardization and improvement, and we also made more efforts than originally planned towards this objective.

The findings of the BARD project, related to these two consequential steps involved in TDR measurement of the soil water content, are expected to improve the accuracy of soil water content determination by existing in-situ and remote sensing dielectric methods and to help evaluate new water content sensors based on soil electrical properties. A more precise water content determination is expected to result in reduced irrigation levels, a matter which is beneficial first to American and Israeli farmers, and also to hydrologists and environmentalists dealing with production and assessment of contamination hazards of this progressively more precious natural resource. The improved understanding of the way the soil geometrical attributes affect its effective permittivity is expected to contribute to our understanding and predicting capability of other, related soil transport properties such as electrical and thermal conductivity, and diffusion coefficients of solutes and gas molecules.

In addition, to the originally planned research activities we also investigated other related problems and made many contributions of short and longer terms benefits. These efforts include: Developing a method and a special TDR probe for using TDR systems to determine also the soil's matric potential; Developing a methodology for utilizing the thermodielectric effect, namely, the variation of the soil's effective permittivity with temperature, to evaluate its specific surface area; Developing a simple method for characterizing particle shape by measuring the repose angle of a granular material avalanching in water; Measurements and characterization of the pore scale, saturation degree – dependent anisotropy factor for electrical and hydraulic conductivities; Studying the dielectric properties of cereal grains towards improved determination of their water content.

A reliable evaluation of the soil textural attributes (e.g. the specific surface area mentioned above) and its water content is essential for intensive irrigation and fertilization processes and within extensive precision agriculture management. The findings of the present research project are expected to improve the determination of cereal grain water content by on-line dielectric methods. A precise evaluation of grain water content is essential for pricing and evaluation of drying-before-storage requirements, issues involving energy savings and commercial aspects of major economic importance to the American agriculture. The results and methodologies developed within the above mentioned side studies are expected to be beneficial to also other industrial and environmental practices requiring the water content determination and characterization of granular materials.

Achievements

The present research project was mostly fundamental and, therefore, it is difficult to evaluate it in terms of increasing yields and economic benefits. Its main subject of research had to do with the effects of geometrical and interfacial soil attributes on the effective permittivity (ε_{eff}) – water content (θ) calibration curve. Based on our findings (articles number 1, 2, 4, 8, 13, 15, 17, 25 in the publication list), these effects are now better understood and predictable. After initializing the experimental investigation of the $\varepsilon_{eff}(\theta)$ relationship, we realized that the first step of the water content determination by the Time Domain Reflectometry (TDR) method, namely the TDR measurement of the soil ε_{eff}, still requires standardization and improvement, and we also made more efforts than originally planned towards this objective (6, 16, 18, 19, 24). The results of these studies are expected to improve the accuracy of the soil ε_{eff} determination with the TDR method and extend its usage to conditions of saline soils (19) and sharp wetting fronts (16, 18) by a more precise waveform analysis (16), an alternative (to rods) parallel plates probe geometry (6), and frequency domain analysis of the time domain waveforms acquired with short probes (19). We believe that the findings of the BARD project, which are related to these two consequential steps involved in TDR measurement of the soil water content, will improve the accuracy of soil water content determination by dielectric methods. This is expected to result in reduced irrigation levels, a matter which is beneficial first to American and Israeli farmers, and also to hydrologists and environmentalists dealing with production and assessment of contamination hazards of this increasingly precious natural resource.

The improved understanding of the way the soil geometrical attributes affect its effective permittivity is expected to contribute also to our understanding and predicting capability of other, related soil transport properties such as electrical and thermal conductivity, and diffusion coefficients of solutes and gas molecules, relevant to the assessment of various transport phenomena occurring in agricultural fields. In addition to the research activities along these planned objectives (darker items in the scheme), we also investigated other related problems (non-colored items in the scheme) and made several contributions of short and longer terms benefits, some of which are listed below:

A methodology and a special TDR probe were developed to use TDR systems for determining also the soil matric potential (in addition to its water content) by either the new developed probe (3), or a reference soil in contact with the soil of interest, in which a regular TDR probe is installed (11). Knowledge of the soil matric potential is important for evaluating water availability to plants and for determining the directions of water flow in the vadose zone.

The TDR method provides also a measure of the bulk electrical conductivity (EC) of the soil (24) and we also made some efforts towards improving the determination of the soil solution EC (salinity), relevant to agronomic and environmental issues, from simultaneous TDR readings of the soil's bulk EC and water content (7, 20, 21).

A methodology had been developed for utilizing the thermodielectric effect , namely, the variation of the soil's effective permittivity with temperature, to evaluate the soils specific surface area (22), a soil attribute essential for plants nutrition management and prediction of soil and ground water pollution processes.

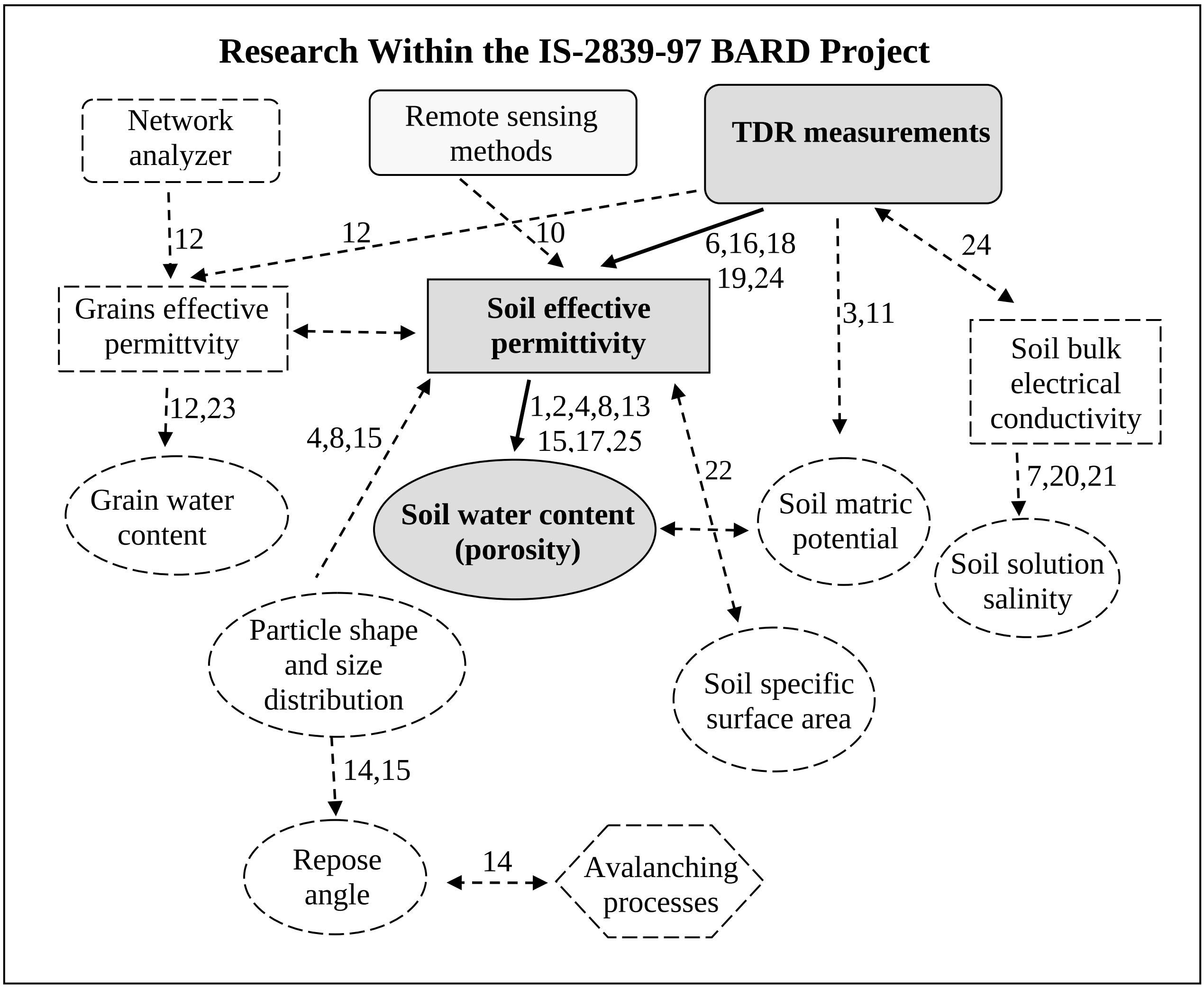
Most of our measurements of the soil permittivity were done with the TDR method. However, as outlined in the proposal we also analyzed theoretically issues concerning remote sensing dielectric methods (10). The findings of this study are expected to improve remote sensing determination of the water content of the soil surface and advance many aspects of irrigation management and other precision agriculture practices, related to the evaluation of evaporation, infiltration and runoff rates on regional scales. In addition they will promote the utilization of remote sensing methods for evaluating soil textural attributes (e.g. the specific surface area mentioned above), required for soil classification.

While studying the effects of particle shape on the effective permittivity of soils and granular matter, we developed a simple method for characterizing particle shape by measuring the repose angle of the granular material avalanching in water (15). This method is expected to be beneficial also to many industrial applications involving granular materials. Along this side study we also recorded and documented some observations on the effects of particle shape and particle size distribution on avalanching processes (14, 15). These empirical findings contributed a bit to our understanding of this yet unresolved physical problem of avalanching (granular flow in general), which is of practical importance for several industrial (granular flow in silos), and environmental (land avalanches) applications. In another side study evolving from investigating particle shape effects on the directional ε_{eff} of anisotropic media (4), the pore scale, saturation degree – dependent anisotropy factor for electrical conductivity was measured (packings of aligned mica particles were used), and a theory was proposed for explaining it and predicting the expected saturation degree – dependent anisotropy factor for the hydraulic conductivity (9). The latter is important for predicting water and contaminants flow in unsaturated anisotropic porous media.

Parallel to studying the dielectric properties of soils we also studied the dielectric properties of cereal grains (12, 23) within a project, originally funded by Campbell Scientific and Harvestmaster (Logan, Utah, USA) and Pioneer Hi-Bred International (Johnston, IA, USA). In addition to TDR measurements of the effective permittivities of packings of cereal grains (mostly corn), frequency domain measurements by a network analyzer were also conducted. The results of this study are expected to improve the determination of cereal grain water content by on-line dielectric methods. A precise evaluation of grain water content is essential for pricing and evaluation of drying requirements before storage, matters that involve energy savings and commercial aspects of major economic importance to the American agriculture.

The research project was carried out with good cooperation among the three BARD investigators (Friedman, Wraith and Or) and two post-docs, who should be credited for the major part of the extensive research activity described above: Scott Jones who worked first with SF in the ARO and then with DO in Utah state University, and David Robinson who worked at the ARO. In the process of this BARD sponsored research project both postdoctoral researchers advanced to full-time positions at Utah State University, Logan, UT (Scott Jones) and at the USDA Salinity Lab in Riverside, CA (David Robinson). According to the original work plan outlined in the research proposal, the American side was meant to deal mostly with interfacial processes and the Israeli side with the geometrical effects determining the soil $\varepsilon_{eff}(\theta)$ relationship, which we did. However, the whole five of us were in continuous contact, updating each other with the upcoming results and exchanging ideas on how to promote the research in the three institutes. In the personal meetings, which took place approximately once a year, we summarized past research stages and planned the next ones. To mention just one example of the mutual benefits resulting from our mode of collaboration, the Israeli findings and developed concepts on the geometrical effects on the effective permittivity of soils and granular materials (4, 8) were utilized by the Americans in their study on the dielectric properties of cereal grains (12, 23). In return, the American findings on interfacial process (bound water), retrieved also from frequency domain measurements, are being utilized and implemented at present to soils. As a result of the collaboration within this working group, a proposal has been submitted to the USDA by Jones, Robinson and Or, to extend previous work on developing methods to measure soil water content in saline soils using TDR techniques. Or and Friedman had also submitted a BARD proposal on another subject (microbial activity and the soil physical properties and conditions).

The results of this wide-ranging BARD project were reported in 31 presentations in professional meetings all over the globe and are going to be published in 22 refereed research articles (14 already published) and 3 review articles.


Research Within the IS-2839-97 BARD Project
Network analyzer
Remote sensing methods
TDR measurements
12
12
10
6,16,18
19,24
24
3,11
Grains effective permittvity
Soil effective permittivity
Soil bulk electrical conductivity
12,23
4,8,15
1,2,4,8,13
15,17,25
22
7,20,21
Grain water content
Soil water content (porosity)
Soil matric potential
Soil solution salinity
Particle shape and size distribution
Soil specific surface area
14,15
Repose angle
14
Avalanching processes

List of Publications

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